AAS 08-107

THE LUNAR SLINGSHOT -- AN ELECTRICALLY POWERED LAUNCHER

Ronald M. Muller *

The Lunar Slingshot is an electrically driven reusable launcher located in close proximity to a North or South pole lunar colony. The design that is presented can launch 1,000 km payloads into a circular 100 km lunar orbit. It can also put a lighter payload into a higher energy trajectory. Slingshots with more launch capacity can be scaled directly from this design. The Slingshot will provide a safe, clean and efficient means of launching many payloads from a lunar polar base. No need to supply fuel from the earth or to use fuel derived from lunar water deposits to launch a satellite from the Moon's surface. Since there is no rocket exhaust, lunar dust is not stirred up by a launch.

The Slingshot is a multi-strand cable many km long that carries a payload at one end and rotates around a central pivot structure that is anchored to the Moon at the other end. An electric motor at the pivot point provides the rotational energy. The plane of rotation is perpendicular to the Moon's rotation axis. Some distance along the cable from the payload and attached to it is a 50 kg bolo mass. A lightweight tether connects the bolo mass to the payload. The payload/bolo cable deployment mechanisms are carried on one end of a cross boom mechanism housing that is attached to the motor shaft. To balance the lateral force on the central pivot point, a heavier counterweight (typically a bag of lunar soil) is deployed from a shorter cable mechanism on the side opposite the payload cable mechanism.

In operation, the slingshot starts with all the cables stowed inside the cross boom central mechanism housing. The electric motor accelerates the cross beam housing with the payload and counterweight attached to their retracted cables to a desired rotational rate. Then, as the motor continues to torque the Slingshot, the power is absorbed by paying out the payload and counterweight cables. When the cable is fully deployed and the desired rotational velocity reached, the payload/bolo masses are released and they go into a 0 x 100 km altitude lunar orbit still tethered together. Simultaneously, the counterweight is released but its velocity is not enough to orbit so it impacts the moon.

After release, the payload and bolo continue to spin about their center of mass. At the first apocynthion, the spacecraft releases the bolo mass. The rotational stored momentum provides the payload with a positive delta-v of 23 m/s circularizing its orbit at 100 km. The bolo is slowed and impacts the moon.

The payloads that Slingshot can orbit can be quite unsophisticated since all delta-v and basic orientation required to achieve orbit is provided mechanically by the Slingshot. This is ideal for launching tanks of bulk propellants manufactured by the colony and/or bags of lunar soil.

* Senior Staff Engineer, Perot Systems Government Services, ronald.muller@psgs.com

INTRODUCTION

Lunar colonies at the north and/or south pole will eventually be built. Solar arrays mounted on nearby highlands will provide continuous electric power. The nearby parts of impact craters that never see the sun probably contain water ice. Using the solar electric power, that ice can be melted, electrolyzed into hydrogen and oxygen and cryogenically stored as liquid rocket fuel. The usual scenario would be to use some of that fuel to launch payloads into a lunar orbit or to some other rendezvous point such as the earth-Moon L1 point. At the rendezvous point the lunar fuel could be transferred to an empty rocket stage to return to Earth or to go to Mars or to some other destination.

The Lunar Slingshot reusable launch facility presented in this paper can reliably put 1,000 kg unmanned payloads into a 100 km circular orbit using only solar electric power. The design uses currently available braided rope for the cables and conservative safety margins. A Slingshot payload can be very simple and low cost because it does not need a rocket propulsion system and an attitude control system to leave the moon's surface and achieve orbit. Also, unlike a conventional rocket launch, it will not raise any Moon dust during the launch.

It is expected that by the time a lunar colony is built, much better fiber will be available. Then a Slingshot will be able to launch payloads into escape trajectories such as to an Earth-Moon L1 or L2 point and directly to planets.

SLINGSHOT HISTORY

The origin of the slingshot as a hunting tool and a weapon has been lost to history, but probably was used long before man figured out how to make stone implements.

Probably the most famous slingshot story is of David killing Goliath[1] dated to around 1063 BC. The slingshot is still used in some parts of the world as a hunting weapon.

The bolo (or bola or boleadora) usually consists of two or more weights attached to each other by cords. A hunter swings the bola around and around and throws it towards the animal he wishes to capture. The cords wrap themselves around the animal's legs and immobilize it.

When the term "slingshot" is applied to the orbital mechanics of satellites, it usually refers to a gravity-assisted maneuver by a satellite passing by a moon or planet. The force of gravity between the larger body and the passing satellite causes a momentum exchange that changes the satellite's velocity vector in some desirable way. The slingshot gravity-assist technique was developed back in the early 1960s by Michael Minovitch, while a student working at NASA's Jet Propulsion Laboratory.[2]

In 1986, I proposed[3] a slingshot that could be built in low earth orbit (LEO). It was to be served by the Shuttle and be able to place multiple 7,370 kg payloads into a geosynchronous transfer orbit (GTO) using an electric motor. The motor torqued against gravity gradient booms. It could give a payload a delta-v of 2378 km/sec boosting it from LEO to GTO. That delta-v is almost identical to the Moon's escape velocity. The paper observed that a similar slingshot could be built on the Moon, but did not develop the idea.

In 1990, D Baker and R. Zubrin[4] described a lunar slingshot launcher as part of a Lunar – Mars architecture study. They showed significant economic advantages that would result from building such a facility. It was sized to launch 10,000 kg payloads.

LUNAR SLINGSHOT DESIGN

Location on the Moon

On the Moon, a Slingshot can only be located close to a pole. This is because only at those two locations can the large momentum vector of the rotating Slingshot mechanism be aligned with the Moon's rotation axis. At all other locations, the Moon's rotation would require the application of a continuous torque to the mechanism's momentum vector to keep the plane of rotation in the local horizontal plane. That is not practical.

The Slingshot central pivot point of the launcher must be mounted on a high lunar surface. The topography around the central pivot must slope downward to clear the cables as they rotate because they droop due to the Moon's gravity. Also the nearby topography must be no higher since the payload's initial trajectory will be horizontal.

The Slingshot's maximum cable length will depend on the available topography. The longer the cable, the lower the g force on the payload, but the more the cable will droop. Figure 1 plots the payload g force and the droop as a function of maximum cable length. Interestingly, the mass of the Slingshot's cables is not a function of cable length.

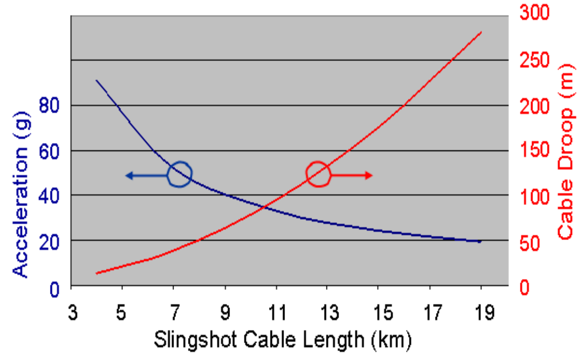

Figure 1 -- Acceleration and Droop vs. Cable Length

The Slingshot mechanism

The Slingshot is a long, multi-strand, tapered cable that carries a payload on its end and uses electric power to rotate it around a vertical axis that is parallel to the Moon's axis. Some distance inboard from the payload, a "bolo" mass is also carried by the cable. Connecting the payload to the bolo is a lightweight tether. The other end of the payload/bolo cable is attached to a rotating mechanism at the top of a vertical tower that is anchored to the moon. The rotating mechanism consists of an electric motor driven shaft oriented parallel to the Moon's axis. The payload/bolo cable deployment mechanism is carried inside a housing mounted across the top of the motor shaft.

To balance the lateral force on the central column, a counterweight made of a bag of lunar soil that is somewhat heavier than the payload is deployed on cables that deploy from the other side of the cross housing. The deployment of the counterweight is controlled to minimize the transverse load on the central column thereby minimizing the unbalance force on the central structure. The picture in Figure 2 is the Slingshot layout for a 19 km long Payload/Bolo Cable. (Note: the vertical droop is exaggerated by a factor of 5 in Figure 2.)

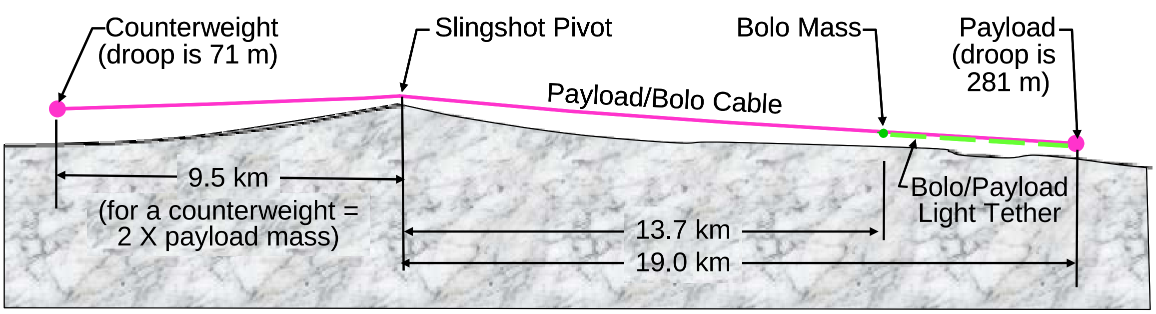

Figure 2 – Slingshot Layout for a 19 km long Payload/Bolo Cable

If the counterweight is twice the mass of the payload/bolo mass, its cable would be twice as strong, but only one-half as long and so it would have the same mass as the payload/bolo cable. The tip velocity would be one-half the tip velocity of the payload/bolo cable. The counterweight is released simultaneously with the payload/bolo to keep the balance. Because it is going much slower, it cannot go into orbit but impacts the Moon some distance from the Slingshot.

The Slingshot cable design

The Slingshot cable is designed to make the probability of catastrophic failure very low. Of particular concern is the meteor environment. Since the Moon has no atmosphere to cause small meteors to burn up, the Slingshot must be built to withstand them. A 1969 NASA Special Publication[5] estimated that at the moon surface, the particle flux could be 40 times greater than in space a few km above the surface. This increased particle flux is caused by a high velocity meteor impacting the moon kicking up multiple lower velocity particles.

Any damage of the cables must be repairable. One way to do this is to make the cables out of multiple individual ropes and to space those ropes sufficiently far apart so that a meteor less than a given design size cannot break more than two of the ropes as it passes.

The design in this paper uses 8 ropes at the payload end of the cable and as one goes back towards the central pivot, additional ropes are added to handle the additional tension load. The number of ropes at each location along the payload/bolo cable is illustrated in Figure 3 for several maximum cable lengths. At all locations along the cable the safety factor is two or more.

To keep the individual ropes spaced apart, a circular graphite-epoxy spacer is robotically clamped to the ropes every 100 m of the payload/bolo cable as the cable is paid out. The 8 rope spacer for a 19 km payload/bolo cable is illustrated in Figure 4. As each additional rope is added, the diameter of the spacer is increased to keep the spacing between adjacent ropes constant. (For the 2X counterbalance example, the spacers would be located every 50 m along the counterbalance cable.)

The spacer holds the ropes apart from each other so that a meteor up to the size of a golf ball cannot break more than two

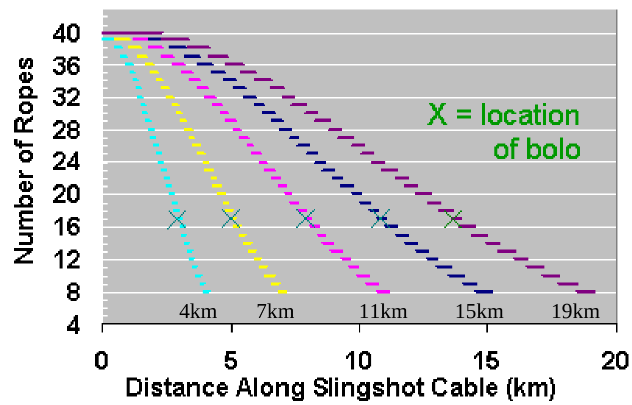

Figure 3 – Step-wise Taper of Slingshot Cable, from left, 4, 7, 11, 15 and 19 km long cables

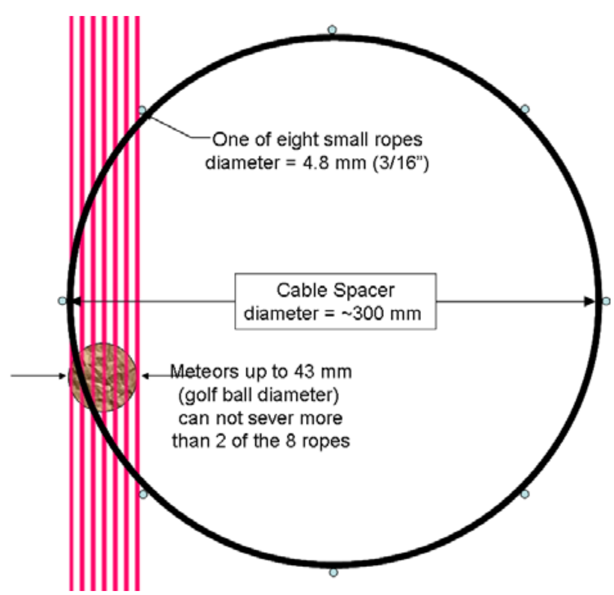

Figure 4 – Cable Spacer Layout for a 19 km Slingshot Payload/Bolo Cable

of the eight ropes. Such a break would not be catastrophic because the safety factor would be at least 1.4. As more ropes are added to the cable, the cable can withstand even larger meteors while maintaining a safety factor somewhat greater than 1. Should a meteor cause a rope to break, the spacers on either side of the break redistribute the tension load among the remaining ropes. They also restrain the travel of the broken rope ends.

If a meteor hits a cable and severs a rope, the cable deployment could be stopped and the rotation slowed to lower the tension and regain safety margin. The Slingshot could then retract the cables until the broken 100 m section reached the central hub. Then the broken ropes could either be robotically joined back together or they could be replaced with spare cables. Then the launch would begin again.

Figure 5 shows the central mechanism housing and the Slingshot with the initial 8 cables just starting to be deployed. The diameters of the ropes and the central housing are exaggerated so that they would be visible in the drawing. The notional solar array shown can turn to face the sun providing continuous power. As drawn, there would some shadowing of the array by the Slingshot housing. This would reduce the power to the Slingshot for a few days.

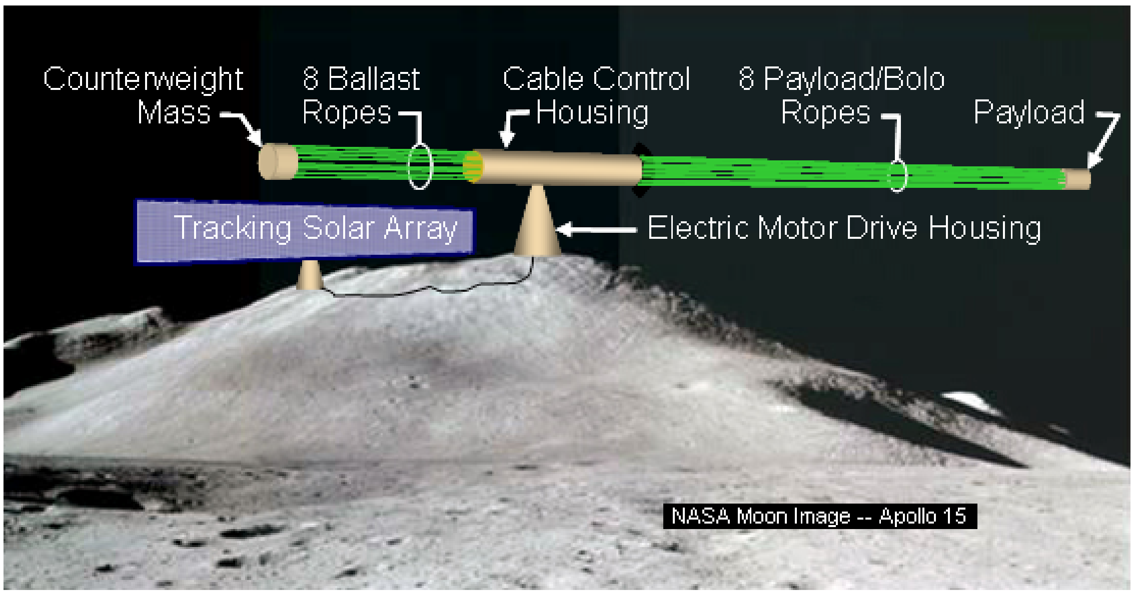

Figure 5 – The Slingshot starting to launch a payload

A SLINGSHOT LAUNCH

Achieving a 0 x 100 km initial orbit

The Slingshot launches two items: a payload and a bolo mass tethered to it. The payload is mounted at the far end of the payload/bolo cable while the lighter bolo is mounted much closer to the central hub. The two are connected by a tether. When the rotational velocity of the center of mass of the payload/bolo combination is 1703 m/s, the 1000 kg payload will be going 26 m/s faster at 1729 m/sec and the 50 kg bolo will be going slower by 460 m/sec or 1243 m/s. When the payload/bolo combination is released, their center of mass will have a velocity of 1703 m/s putting them into a 0 x 100 km altitude orbit.

Circularizing the initial orbit

After the Slingshot releases the payload/bolo combination, they continue to rotate about their center of mass. When they reach apocynthion, the payload releases the bolo tether. This gives the payload the needed 23 m/s orbital velocity increase to circularize its orbit. The bolo mass gets a 460 m/sec delta-v in the direction opposite the orbit velocity and it and the tether impact the Moon. If just a simple tether release is used, the payload will continue to spin. If a non-rotating payload was desired, the bolo tether would be wrapped around the payload so that when it is released, it removes the payload's rotational momentum.

Note that payloads launched by any other mechanism that launches a payload horizontally, such as a rail gun, must provide a means of raising pericynthion at the first apocynthion. Otherwise after one orbit, the payload will return to the launch site and could impact the launcher!

Placing many payloads in a "string of pearls" configuration

To be of service to missions that need more lunar product than can be delivered by one Slingshot payload, it will be necessary to launch multiple payloads into lunar orbit and space them apart like a "string of pearls" in the same orbit. This will minimize the propulsion needed to rendezvous and dock with each payload in turn. Since all Slingshot payloads will have an inclination of 90 degrees, it is just a matter of picking the right instant in the Slingshot's rotation to put another payload in exactly the same orbit plane and phased with the payloads already in orbit. In other words, a Slingshot can precisely load up one orbit plane with multiple payloads so a user mission will have an easy rendezvous with each in turn.

Getting the Slingshot ready for the next launch

When the masses of the payload, bolo and counterweight are released, the cables will experience two motions. The release reduces the gravity induced droop. This will cause the cables to snap upward. Simultaneously, the reduction of cable tension will reduce the stretch in the cables causing them to shorten. It is expected that the braded cable weave with the plastic overcoat (discussed below) will quickly damp both of these motions.

Once the cables take up a stable shape, the motor will become a generator and start to slow the Slingshot. The power produced could be fed into a local power grid. The generator continues to remove energy until the cables are fully retracted. The cable spacers are robotically detached and stowed as the cable is retracted. Also during the retraction, each rope is inspected for damage and repaired or replaced as needed. When all the cables are fully retracted, the Slingshot brakes to a full stop. A new payload, a new bolo and a new counterweight can then be attached, the generator becomes a motor again and another Slingshot launch can begin.

SLINGSHOT CABLE MASS

Cables made of fiber available today

This paper assumes a braided Zylon® rope which is commercially available today from Cortland Cable Company. Its specific strength is about 2 Newton-km/gram after being braided, terminated and over-coated with a thin, flexible plastic jacket. The jacket serves two needs: one, it will protect the fiber from the sun's ultraviolet light and two, it will prevent any abrasive Moon dust from becoming entrained within the fibers and causing wear as they are deployed and retracted.

For a given payload mass and velocity and Slingshot cable safety factor, the cable mass depends directly on the rope's specific strength. For a payload mass of 1000 kg, a bolo mass of 50kg, a cable of braided Zylon®, and a safety factor of 2, the Payload/Bolo cable and the Counterweight cable will each weigh about 12,200 kg including the spacers.

Cables made of fiber available in the future

It is quite likely that by the time a lunar polar colony is built and there is the need for a payload launcher such as a Slingshot, rope with a better specific strength will be commercially available. This will greatly enhance a Slingshot's capability. For instance, for a modest improvement of specific strength from 2 to 3.6, the same mass Slingshot can launch a 1000 kg payload into lunar escape and to the Earth-Moon L1 or L2 points.

Much more dramatic improvement in rope specific strength is expected as a result of NASA's Space Elevator[6] part of the Centennial Challenges program. Any gains in specific strength for a Space Elevator when applied to a lunar Slingshot will translate into a much higher payload mass and/or velocity for the same Slingshot mass. For example, if the minimum specific strength needed for a Space Elevator of 35 is achieved, a 12,200 kg lunar Slingshot with cables of that specific strength will be able to launch a payload of 25,000 kg to lunar escape velocity. Curves illustrating Slingshot performance for various values of specific strength rope are shown in Figure 6.

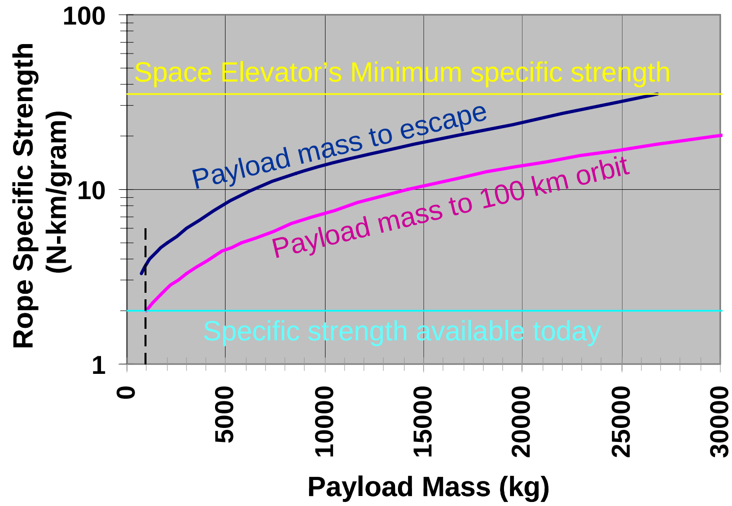

Figure 6 – Slingshot Performance vs. Rope Specific Strength

Keeping Moon dust out

If any Moon dust is kicked up by activity at the colony, it must be kept out of the Slingshot's mechanisms because it is very abrasive. To do this, these mechanisms are contained inside a lightly pressurized housing. Also, the ropes might pick up dust during operation and they must be cleaned as they are retracted into the housing. Brushes mounted around the rope entrance holes will do this. Note that the Slingshot's rotation is always kept fast enough to keep the ropes well above the surface during their extension and retraction. The only time the Slingshot can be stationary is when all cables are fully retracted.

PAYLOAD DESIGN

A Slingshot payload can be very simple because it does not need any conventional propulsion system or an attitude control system to achieve orbit. It is particularly suited to moving bulk products from a lunar base into orbit. For launching that kind of material, the payload could be as simple as a container for the bulk material. The only electronics needed would be a simple timer that inhibits the bolo tether release until one-half orbit period elapses. Then it removes the inhibit and, based on a spin phase calculation, the bolo is released at the correct point in the spin. The spin phase calculation would be a preset angle after a sun sensor pulse.

If water is available, both liquid oxygen and liquid hydrogen could be manufactured and loaded into insulated tankage that is overwrapped with the same Zylon® fiber used to make the Slingshot's cables. Zylon® has very good mechanical properties at these low temperatures. One commercial use of Zylon® is as a strength member inside superconducting magnets at liquid helium temperatures.

Lunar soil can be orbited using a bag made of Zylon® fiber. Once in lunar orbit, the soil could be incorporated into any manned satellite to provide long-term radiation protection for astronauts.

LAUNCHING TWO PAYLOADS SIMULTANEOUSLY

The design presented above uses a ballast mass to balance the lateral loads on the central column. An alternate design would substitute another payload for the ballast mass. By placing two payloads into orbit at the same time, the launch capacity of the Slingshot would be doubled. Eliminating the ballast mass also eliminates the stirring up of moon dust when it lands.

The counterweight would be replaced by a second payload/bolo combination. The two payloads would be released simultaneously. They would both be in the same orbit plane, but going in opposite directions. To avoid a collision, the second payload mass would be different from the primary payload mass and its cable length would be adjusted so as to keep the balance. For instance, if the second payload were less massive, its cable would be longer. Then when the second payload was released simultaneously with the primary payload, its velocity would be higher so its final orbit would be higher than the primary payload thereby avoiding any collision possibility.

When higher specific strength cables are available, a dual launch could send one payload to the Earth-Moon L1 point and the other to the L2 point. It typically takes only a few meters per second delta-v to then move one payload to the other payload's L point.

CONCLUSION

Once a lunar polar colony is built, a Slingshot could provide a safe way to orbit lunar products from that colony. A Slingshot payload could be very simple since no propulsion system, no fuel and no attitude control system would be needed to get the payload into orbit. Since no conventional propulsion is used, no lunar dust is kicked up by a Slingshot launch.

The launch would include a bolo mass tethered to the payload. After one-half orbit, the bolo would be released and the stored rotary momentum would boost the payload into a circular orbit while simultaneously causing the bolo to return to the Moon's surface. The slingshot cables are made up of multiple ropes that are spaced apart from each other. This allows the Slingshot to survive collisions with all meteors except the very infrequent, very large meteors. If individual ropes are severed by a meteor, the Slingshot will be able to robotically repair itself and continue to launch satellites.

ACKNOWLEDGMENT

Doug Bentley of the Cortland Cable Company provided advice and information about suitable ropes for use on a Slingshot.

This work was partly funded by a task on contract NNG04DA01C with the NASA Goddard Space Flight Center.

REFERENCES

[1] The story of David killing Goliath with a slingshot can be found in 1 Samuel, chapter 17 of the Bible

[2] See the web site http://www.gravityassist.com/ for a complete description of this invention

[3] Ronald M. Muller, "The Slinger—An In-Orbit Booster Facility," AIAA 86-2175-CP

[4] D. Baker and R. Zubrin "Lunar and Mars Mission Architecture Utilizing Tether-Launched LLOX" AIAA 90-2109

[5] NASA SP-8013 "Meteoroid Environment Model – 1969 (Near Earth to Lunar Surface)

[6] For information about the Space Elevator Centennial Challenge, see http://www.spaceward.org/elevator2010